TYPES OF PRISMATIC STRUCTURE IN IGNEOUS ROCKS[1]

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The question of the cause of columnar or prismatic jointing in igneous rocks was thought to have been satisfactorily settled by the writings of Thomson, Mallet, Bonney, Iddings, and others, until it was reopened recently by the investigations of several French physicists. As the subject seems to be in need of further discussion and experimental study, I have brought together observations on several hypotheses of prismatic jointing, hoping to show that the study of these structures may yield much more precise information than is now available as to the original conditions of occurrence of the igneous rocks in which such structures are found.

CRYSTALLIZATION HYPOTHESIS

The first hypothesis as to the origin of prismatic structure which had any experimental or observational basis was that of Gregory Watt,[2] and may be entitled the "crystallization hypothesis." Watt, in 1804, observed that a large mass of basalt which he had melted down in a reverbatory furnace crystallized radially from centers which were fairly regularly spaced in a horizontal plane; the intersections of these radially growing fibrous bundles formed a network of hexagonal partings through the mass, leading Watt to the conclusion that this manner of crystallization, by its vertical extension upward from the base of a mass of basalt, must have been the cause of the prisms found in the Giant's Causeway, Fingal's Cave, and elsewhere.

[1] Presented before the Geological Society of Washington, April 28, 1915.

[2] Gregory Watt, "Observations on Basalt, and on the Transition from the Vitreous to the Stony Texture," etc., *Phil Trans.*, 1804, pp. 279–314. Watt also explains clearly the contractional origin of such structures as mud and starch prisms.

This explanation seems to have been satisfactory to many of the earlier authors of geological treatises,[1] but before many years had passed doubts began to arise as to whether this process could have been an efficient cause of the numerous cases of columnar structure which began to accumulate in geological literature as travel became more extensive and observations multiplied. James Thomson[2] in 1863 urged that contraction of a homogeneous mass was a sufficient cause for all columnar structure, and that the hypothesis of crystallization from centers was unnecessary and improbable. Mallet[3] discussed the contraction hypothesis in detail, showing how it would account, in his opinion, for all of the structures found in columnar rocks. Bonney,[4] Iddings[5] and others have followed the same lines of argument.

CONTRACTION HYPOTHESIS

The radial-contraction hypothesis is still the explanation generally accepted by the textbooks, and perhaps applies in the majority of cases of prismatic structure. But a much more complete discussion of this hypothesis than has yet been published could be profitably made, for there has been no attempt at any quantitative application of it to actual occurrences. It has served hitherto simply as a qualitative explanation. The relation of the size, shape, curvature, jointing, and other properties of the columns to the original temperature, viscosity, and rate and manner of cooling of the rock is capable of more exact definition.

For instance, the time factor in cooling in its relation to the elastic properties of the rock does not seem to have been considered

[1] More or less vaguely associated with this definite hypothesis was the idea of a "concretionary force" which is frequently referred to. The idea that columns might be due to the mutual compression of actual spheroids of lava (now understood as "pillow" lava) was also more or less confused with the crystallization hypothesis. Watt's idea of the matter seems to have been perfectly clear, but Mallet, for instance, misunderstands Watt's "mutual compression of spheroids" to mean actual compression (*Phil. Mag.*, L [1875], 221–24); the words "mutual interference of radially growing spheroids" state Watt's meaning more clearly.

[2] *Brit. Assoc. Rep.*, 1863, Abstract, p. 89.

[3] *Phil. Mag.* (4), L (1875), 122–35, 201–26.

[4] *Quar. Jour. Geol. Soc.*, XXXII (1876), 140–54.

[5] *Amer. Jour. Sci.*, XXXI (1886), 321–31.

in previous discussions. If the mass is cooling slowly, the crystallized shell may be able to adjust itself by a slow movement to the stress produced by contraction, so that the strain does not for some time pass a given value. If the cooling is rapid, on the other hand, the strain may be rapidly raised through the inability of the mass to flow as rapidly as the stress is applied. Under conditions of rapid cooling, therefore, the temperature at which the stresses become sufficient to produce rupture will be higher than under conditions of slow cooling.[1]

Another point concerns the conditions of rupture. Published discussions of formation of columns by contraction have tacitly assumed that the condition of rupture is that the *extension* shall exceed a certain limiting value. This is only one out of several possible conditions of rupture. Various hypotheses have been proposed by physicists (limiting tension, limiting positive or negative strain, limiting shear), of which the best founded experimentally is that of Tresca and Darwin, according to which rupture occurs when the maximum difference of the greatest and least principal stresses reaches a certain limiting value.[2] Although the acceptance of this condition of rupture as the fundamental one does not simplify the problem of calculating the actual physical magnitudes of temperature, temperature gradient, stress, and strain in any given case, yet it should permit a more complete analysis of the kinds of structure that will result from different conditions of cooling. Such an analysis is, however, beyond the scope of the present article.

CONTRACTION OF PHYSICALLY HETEROGENEOUS MATERIAL

Prismatic structure is very common in materials which are heterogeneous as regards their state of aggregation (such as mud and wet starch), that is, in which solid matter is suspended in or mixed with a liquid. It is a question whether the formation of a prismatic structure in such materials is strictly comparable with most cases of contraction prisms in igneous rocks. The principal

[1] The above-mentioned effect of the rate of cooling is quite distinct from the commonly recognized effect, which appears in the *temperature gradient* away from the surface of the cooling mass.

[2] Love, *Theory of Elasticity*, 1906, p. 119.

difference is in the strength of the materials. Very considerable stresses may accumulate in a glassy or crystalline rock before rupture occurs, and when it does occur, the crack extends suddenly a considerable distance into the mass. A layer of wet mud, on the other hand, accumulates practically no stresses, as the forces of cohesion and liquid surface tension to be overcome are very small. The cracks therefore form much more gradually, and grow little by little as desiccation proceeds. They have even been observed to form under water,[1] probably as a result of freezing and melting.[2]

It is possible that some basalt prisms have been formed in the same way as the slowly formed mud cracks, by the slow shrinkage of a material which is partly solid and partly liquid, for the normal course of crystallization of an igneous rock consists in the separation of certain portions as crystals while the remainder stays liquid until a lower temperature is reached. It has been commonly observed, however, that the boundaries of contraction columns frequently cut across the crystals of the rock, showing that solidification was practically complete before the crack formed.

An example of prismatic, although not columnar, structure produced in this manner is probably to be found in the "apparent sun-crack structure in diabase," described by Wherry as occurring in the upper surface of the great diabase sill of Pennsylvania, west of Philadelphia.[3] He explains it as due to contraction jointing followed by the penetration of still liquid material into the cracks from below. At first sight this occurrence has some of the characteristics of prismatic structure due to liquid convection accompanied by segregation, but a re-examination of the structure by Dr. Wherry and the author in May, 1915, showed that the angles and polygons

[1] Moore, *Am. Jour. Sci.*, XXXVIII (1914), 101–2.

[2] Mud cracks may also belong to the other types of columnar structure. Where the deposit is very fine grained and homogeneous, the walls of the columns may show the feathery patterns characteristic of a fractured solid, resulting from breaks (either sudden or slow-growing) which occurred when the material was nearly dry, and indicating the existence of tensional stresses. On the other hand, a prismatic structure of apparently convectional origin has been observed by Guillaume (*Soc. Franc. Phys., Bull. Seances*, 1907, pp. 50–51) in mud flows in sub-Arctic regions.

[3] E. T. Wherry, "Apparent Sun-Crack Structures and Ringing-Rock Phenomena in the Triassic Diabase of Eastern Pennsylvania," *Acad. Nat. Sci., Philadelphia, Proc.*, LXIV (1912), 169–72.

are those produced by contraction, not by convection (see p. 225). A photograph of the occurrence is shown in Fig. 1. An examination by Wherry of the cross-section of one of the small "dikes" shows that it has an irregular boundary, that it grades off without a sharp break into the surrounding rock, and that it is more coarsely crystalline than the surrounding material. It appears to be, therefore, a case of prismatic structure due to contraction in physically heterogeneous material, and quite distinct from the usual type of contraction prisms. Dr. N. L. Bowen, of this laboratory, informs me that he has seen a similar structure in the upper surface of a diabase sill north of Lake Superior.[1]

CONVECTION HYPOTHESIS

E. H. Weber[2] described in 1855 a phenomenon observed by him on microscope slides on which a solid was being precipitated from alcohol-water mixtures. The liquid was observed to circulate and to divide itself up into regular polyhedral cells. A similar phenomenon was observed by James Thomson[3] in 1882, in a soap solution. It remained for the French physicist Bénard,[4] in 1900, to make a really thorough study of the subject, and his experiments have brought out a number of new and interesting facts.

A polygonal structure is easily produced in a layer of liquid which is shallow in comparison with its horizontal extent, and which is losing heat from its upper surface or is gaining heat from its lower surface. If the top surface is cooler than the bottom, then the colder and denser liquid at the top tends to sink and the warmer bottom layer to rise, and convection currents must be set up. If the conditions are uniform and constant, a *steady state of flow* of some kind must ultimately be set up. In a flat liquid sheet of indefinite extent this state of flow must take the form of parallel rising and descending currents, and these will flow with minimum

[1] Canada, Bur. Mines, *Ann. Rep.*, XX (1911), 125–26.

[2] *Pogg. Ann.*, XCIV, (1855) 452–59.

[3] *Phil. Soc. Glasgow, Proc.* XIII, (1882), 464–68. Thomson recognized the similarity of the pattern to that of the Giant's Causeway.

[4] H. Bénard, *Les tourbillons cellulaires dans une nappe liquide*, etc., thesis, Paris, 1901; *Rev. gén. Sci.*, XI (1900), 1261–71, 1309–38.

FIG. 1.—Prismatic structure due to contraction in physically heterogeneous material. Top of diabase sill west of Philadelphia, Pennsylvania.

friction only when they divide the liquid into hexagonal cells, as can be shown by the same line of argument as is used to prove that a uniform shell, under tension due to its own contraction, breaks with minimum energy expenditure when it divides into hexagons.

Fig. 2 is a cross-section of one of these hexagonal cells, showing how the currents rise in the middle of each prism and flow down at

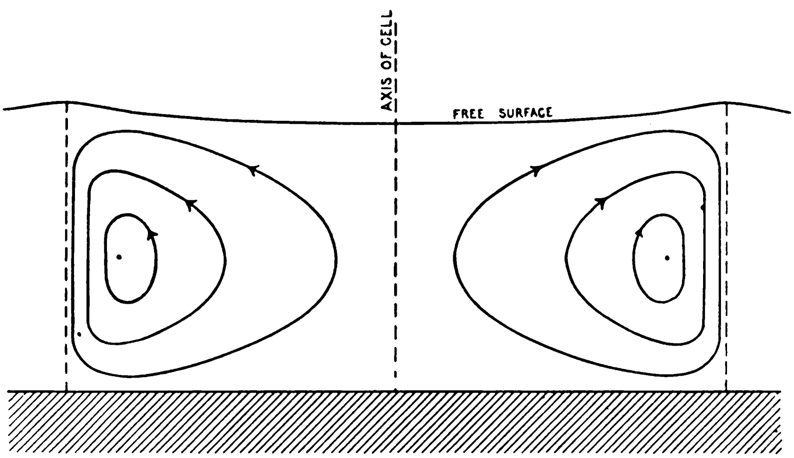

FIG. 2.—Cross-section of a hexagonal cell, showing how the currents rise in the middle of each prism and flow down at the boundaries.

the boundaries. The contour of the surface of the liquid is exaggerated in the figure, but the relief is quite sufficient to permit the structure of the circulating liquid to be observed by various optical methods. Fig. 3 shows three examples of these structures in a melted wax, taken under different conditions of temperature and thickness and before the final steady state of circulation had been attained.

A state of subdivision into irregular cells of from four to seven sides is attained in a few minutes, even in a viscous oil. These cells then join and subdivide repeatedly until finally, if the conditions are constant, a perfect system of hexagonal cells is produced. Even when the liquid is originally in motion, convection cells form which show little or no trace of the original direction of movement of the liquid as a whole.

Waxes and oils were used for most of Bénard's experiments, because at his working temperatures of 100° and lower the requisite conditions as to viscosity and low volatility could best be obtained with these materials. By suspending in them finely powdered substances such as graphite or lycopodium, Bénard was able to show visually and to photograph the cells produced, without the aid of special optical devices.

As is to be expected, the dimensions of the cells depend upon the thickness of the liquid layer, the temperature difference between top and bottom, and the viscosity and temperature of the liquid.

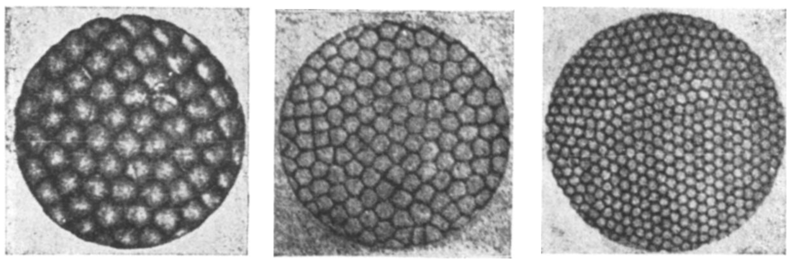

FIG. 3.—Three examples of hexagonal cells formed in a melted wax, taken under different conditions of temperature and thickness and before the final steady state of circulation had been attained.

In a given liquid at a given temperature, and at a constant temperature difference, the ratio of diameter to height is found to be constant. Other laws governing the form and size of the cells were found by Bénard, but it is unnecessary to discuss these in detail.

Following Bénard, Dauzére[1] in 1907 showed that crystallization in salol and wax mixtures begins on the boundaries of the convection cells. A mixture of beeswax and stearin, on solidifying, separates spontaneously into hexagonal prisms coinciding with the original convection cells. In pure stearin, also, crystallization begins at the corners of the cells. In every case the cells leave a permanent record of their existence in the crystallized solid, although in some cases the structure is quite invisible, and only

[1] C. Dauzére, *Jour. physique*, VI (1907), 892–99; VII (1908), 930–34; *Assn. franc. av. sci.*, 1908, pp. 289–96.

appears when the wax is bent. Dauzére pointed out the strong probability that certain symmetrical columns in Auvergne have been due to convection in the basalt in which they are formed.[1]

In a horizontal sheet of molten rock which has come to rest after extrusion or intrusion it is obvious that we have some at least of the conditions necessary for the formation of convection cells. If the cells succeed in leaving any permanent record of themselves when the sheet solidifies, then subsequent contraction may bring out the structure by cracking the rock along the boundaries of the cells.

In general there are two ways in which the convection cells might impress themselves on the crystallized rock. In the first case the axes of the liquid convection cells and of the solid prisms are coincident. Bénard found that a finely powdered substance which is heavier than the liquid tends to gather on the bottom of the vessel in little heaps situated on the axes of the convection cells, giving an appearance from above of uniformly spaced round spots. A floating substance, on the other hand, gathers along the boundaries of the cells at the surface. A substance in suspension gathers within the interior portion of the closed curves of Fig. 2, so that the liquid shows transparent both on the axes and along the boundaries of the cells. In a mixture, therefore, in which different crystalline phases are separating at different temperatures, a certain amount of segregation is to be expected, and the solid prisms will coincide with the convection cells.

In a substance which crystallizes as a unit, on the other hand, whether it be a pure substance or a considerably undercooled mixture, prisms may be formed without segregation. Bénard observed that in spermaceti the crystallization began at the corners of the cells. In pure stearin Dauzére found that crystallization beginning at centers on the cell boundaries extended uniformly in all directions until the growing cylindrical groups intersected to form prisms. It is evident that in this case the prisms will not coincide with the convection cells, but will nevertheless be symmetrical and regularly spaced.

[1] C. Dauzére, *Assn. franc. av. sci.*, 1908, pp. 436–38; also Longchambon, *Bull. Soc. Geol. Fr.*, XIII (1913), 33–38.

It is of interest to note that this convection-crystallization hypothesis explains the original observation of Watt on the formation of columns in a cooling artificially melted basalt mass (see p. 215). He accounted for his columns on the assumption that they were produced by the mutual interference of radially growing crystal bundles, uniformly spaced in a horizontal plane. Why the crystallization centers should be uniformly spaced he was unable to say. The existence of convection prisms in the still liquid basalt provides the missing link in the series of phenomena. Crystallization may have begun at the axes of the convection prisms where a few early separating crystals had collected, or at the corners as observed by Bénard; in either case the crystallization centers would be uniformly spaced horizontally.[1]

If liquid convection is really the cause of all or any of the familiar naturally occurring basaltic columns, then it is important to know what criteria will help to decide the question in a given case. Furthermore, a systematic examination of natural columns will throw light on their history, whatever may be their mode of origin. What are the important characteristics of a given occurrence which should be observed in the field?

CHARACTERISTICS OF CONTRACTION AND CONVECTION PRISMS

1. *Attitude.*—The original attitude of columns formed by convection should be vertical, or very nearly so. Contraction columns, on the other hand, are usually perpendicular to a cooling surface; irregular conditions of cooling, furthermore, may cause them to curve in a great variety of ways.

2. *Dimensions.*—Convection columns should be much wider, in proportion to their length, than contraction columns, which are commonly very long and narrow. The columns at Murols described by Dauzére are 1.5 to 2 m. wide and 5 to 10 m. high; those measured by O'Reilly in the Giant's Causeway are 0.4 to 0.5 m. in width; the Causeway columns vary from 3 to 25 m. in total height. Scrope describes columns near La Queuille as much as 5 m. in diameter, and 10 m. or less in height.[2] The common contraction

[1] See Longchambon, *Bull. Soc. Geol. France*, XIII (1913), 33-38.

[2] *Volcanoes of Central France*, London, 1858, p. 136.

columns, on the other hand, are usually about 0.2 m. or less in diameter; their length is often 20 m. without a joint, and their total length may be over 40 m. It should be noted, however, that the composition of the rock may have a considerable effect on the size of columns under given conditions of cooling, the more salic rocks forming larger columns than the more femic rocks.

3. *Shape of cross-section.*—Convection columns, if perfect, should all be hexagonal. The more uniform the conditions have been, the greater the proportion of hexagons; in any case, the hexagonal sections will be in the majority. Seven-sided figures will be common, produced by the trunkation of one angle of a hexagon; pentagons will also occur frequently, by the elimination of one side of a hexagon. But three- and four-sided figures will be very rare.

In contraction columns, on the other hand, pentagons are likely to be the prevailing type, and four-sided figures are fairly numerous, while hexagons become less important. This distribution of polygons arises from the fact that a mass cracking under the stresses of its own thermal contraction, although theoretically it should break into perfect hexagons of equal area, actually tends to yield by the formation of master-cracks which are then joined up by the formation of shorter cracks.[1] An example of thermal contraction prisms on a large scale is seen in the soil polygons of Arctic regions; a map of a set of these polygons, in a recent article by Leffingwell,[2] shows clearly the contraction-type fissures described above.

The relative frequency of polygons in some of Bénard's artificial convection cells,[3] in the Giant's Causeway,[4] and in a columnar dike[5] is shown in Table I.

[1] "The rock may rather be said to be divided into numerous perpendicular fissures, than to be prismatic, although the same picturesque effect is produced."—Lyell, description of Torre del Greco.

[2] E. De K. Leffingwell, *Jour. Geol.*, XXIII (1915), 653.

[3] The photograph used for this computation was one taken while the liquid was cooling and the polygons were undergoing gradual changes, leading to the formation of 5- and 7-sided figures. Under steady conditions of heat flow the cells were hexagons almost without exception.

[4] J. P. O'Reilly, *Roy. Irish Acad. Trans.*, XXVI (1879), 641–734.

[5] A. Geikie, *Ancient Volcanoes of Great Britain*, illustration, p. 459.

Bénard[1] has recently shown photographically the identity of pattern between his convection cells and the cross-section of the basalt columns of the flow of Estreys (Haute-Loire), and has also pointed out the qualitative differences between this pattern and that produced by contraction.

TABLE I

COMPARATIVE FREQUENCY OF POLYGONS (PERCENTAGE)

No. of Sides	Artificial Cells	Giant's Causeway		Columnar Dike
		Along a 50-Meter Line	Within Measured Area	
3	0	0	0	5.2
4	5.5	2.0	3.5	28.4
5	36.3	30.7	24.8	43.1
6	45.2	47.1	50.5	20.7
7	12.7	19.6	19.2	2.6
8	0.3	0.6	2.0	0
Total number counted	292	153	206	116

4. *Frequency of angles.*—The angles of convection columns should approximate to 120°, while contraction columns will have a large proportion near 90°. While the frequency of angles is a much more logical criterion than the frequency of different polygons, it is much more difficult to apply on account of the large number of angular measurements to be made. Such a series was made with great care by O'Reilly on the Giant's Causeway, and I have summarized his results in Table II. O'Reilly's deduction from his

TABLE II

FREQUENCY OF ANGLES IN 206 POLYGONS OF THE GIANT'S CAUSEWAY

Range	No. of Occurrences	Range	No. of Occurrences
64° to 75°	9	115° 30′ to 125°	238½
75° 30′ to 85°	19½	125° 30′ to 135°	236½
85° 30′ to 95°	56½	135° 30′ to 145°	143
95° 30′ to 105°	103½	145° 30′ to 155°	18½
105° 30′ to 115°	215	155° 30′ to 175°	5

measurements was that the form of the columns had been governed by the principal angles of the constituent minerals of the basalt, a view which has not met with general acceptance.

[1] *Compt. rend.*, CLVI (1913), 882–84.

5. *Difference in composition and texture between the axis and the periphery of the columns.*—Obviously, no variation whatever should appear in contraction columns. If the columns are due to convection, however, there might or might not be a differentiation, depending upon whether the rock crystallized practically as a unit, or whether it crystallized in stages which permitted of segregation in the convection cells (see p. 223).

In 1914 Dr. H. S. Washington, of this laboratory, examined, in the museum of the University of Catania, a polished section of a column from one of the prehistoric basaltic flows of the Mount Etna region, and observed no variation of texture across the section. From their shape and manner of occurrence, these columns at Etna would seem to be due to pure contraction, and no variation is to be expected.

On the other hand, evidence is not lacking in geological literature of what seems to be a differentiation between the border and axis of some basalt columns. Scrope, in his description of the volcanoes of central France, states that "occasionally (as for example at La Tour d'Auvergne, in the Mont Dore), the columns show a cylinder of compact black basalt within a prismatic case of lighter colour and looser texture, a segregation of dissimilar matter having accompanied the concretionary action."[1] Delesse[2] made in 1858 an interesting comparison of the density of the interiors and exteriors of a variety of columns, the results of which are shown in Table III. Here again a difference between the interior and exterior is indicated in some of the columns, though not in all. Unfortunately the source of the samples which showed small differences is not stated; it may be that they are columns of the narrow contraction type. Delesse took care to assure himself that the differences were real and were not due to weathering of the columns, but it is not impossible that the differences are really due to weathering, since he had not the modern microscopic facilities for examining the individual minerals in thin section.

[1] *Volcanos*, 1862, p. 100. In speaking of "concretionary action" Scrope seems to be referring to the rather vague hypothesis of columnar structure which prevailed at the time (see note, p. 216).

[2] Delesse, "Variations dans les roches se divisant en prismes," *Compt. rend.*, XLVII (1858), 448–50.

The regularity and symmetry of the columns of the Giant's Causeway suggests the convectional origin. It seemed of interest, therefore, to examine a polished cross-section of one of these columns for evidence of differentiation. Through the kindness of Dr. G. P. Merrill, of the United States National Museum, a polished section was cut for us from a Giant's Causeway column in the Museum, and also one from a column from near Bonn on the Rhine.

TABLE III

DIFFERENCE IN DENSITY BETWEEN AXIS AND SURFACE OF BASALT COLUMNS (DELESSE)

	Density		Difference of Density
	Center	Outside	Per Cent
Trachyte, Iceland	2.494	2.478	0.64
Trachyte, Isle Ponce	2.469	2.439	1.21
Phonolite, Isle Lamlash	2.541	2.509	1.26
Trap, Antrim	2.911	2.857	1.85
Basalt	2.930	2.933	−0.10
Basalt	3.030	3.030	0.00
Basalt	2.924	2.916	0.27
Basalt	3.053	3.030	0.75
Basalt	3.044	3.008	1.18

The Bonn column was five-sided, with a maximum cross dimension of 18 cm. The cross-joint near which the section was cut showed fracture lines radiating from one corner, and the joint passed straight across. What appeared to be an inclusion about 16 mm. in diameter showed near the center, and another of similar size seemed to have been cut in two by one face of the column. A sharp weathered zone 3 mm. wide showed clearly, but no other difference between center and border appeared.

The Giant's Causeway column was also five-sided, with a maximum cross-dimension of 37 cm. The section was cut near the convex side of a shallow ball-and-socket joint; the fracture of this joint seemed to have radiated from the *center*, not from any point of the border. The rough surface gave an appearance of finer grain at the border than at the center. On the polished face, however, no such gradation was visible. There was a sharp weathered zone 3 mm. wide, inside of which was a zone varying from 6 to

22 mm. in width, with an ill-defined wavy border. This also may have been due to weathering. Within the central eighth of the area appeared 5 amygdules from 2 to 4 mm. in diameter, and filled with a greenish opalescent mineral. Five others, from 1 to 2 mm. in diameter, appeared in the remaining seven-eighths of the area, none being closer than 25 mm. to the border. The section therefore offers no decisive evidence of a differentiation, although markedly different in character from the Bonn column.

6. *Types of cross-jointing in the columns.*—A differentiation due to convection might be expected to affect the cross-joints of the columns. The peculiar convex-concave or cup-and-ball joints are seldom found in irregular narrow columns of the typical contraction type, and might have some direct connection with a convection structure. Another type of cross-jointing of columns is the "platy" variety, which is sometimes very regular; its origin has not been satisfactorily explained from the physicist's standpoint.

Certain special peculiarities of the cross-jointing may also have to do with the mode of origin of the columns. For instance, James Thomson[1] observed that the symmetrical concave-convex joints of columns from the Giant's Causeway have their origin in a small spot or knob which lies at or near the axis of the column, and differs in texture and hardness from the rest of the rock; from this origin the crack has spread outward, as shown by the radial fracture lines. This same form of fracture has just been described above, as occurring in the National Museum's specimen from the Giant's Causeway. Dauzére mentions the same peculiarity in the columns at Murols, and compares it with the core (*noyau*) which forms in the convection prisms of his wax-salol mixture.

There seems to be good foundation for the opinion that some sort of original structure is responsible for the spheroidal weathering of columns, and that it is not due solely to the rounding off of jointed blocks by weathering, as some have claimed. Thus Bonney cites numerous examples of spheroids formed from columns which showed no cross-joints whatever.[2] Whether these latent spheroids have any connection with the manner of growth of the column it is

[1] *Belfast Nat. Field Club, Ann. Rep.*, VII (1869), 28–34.

[2] *Quar. Jour. Geol. Soc.*, XXXII (1876), 140–54.

as yet impossible to say. Longchambon[1] suggested that the superimposed spheroids are due to a breaking up of long liquid convection cells into a number of shorter ones, each with its own local circulation, but there is no experimental evidence to support this.

7. *Irregularities of faces of prisms.*—Some basalt prisms show the "feather-patterns" characteristic of fractures in homogeneous solids. Their occurrence points strongly to a purely contractional origin. They have been observed in the joint planes of slates, and have been made the subject of an interesting study by Woodworth.[2]

SURFACE STRUCTURE PRODUCED BY INTERNAL EXPANSION

In addition to the prismatic structures produced by contraction and convection or by convection combined with crystallization and contraction, still another type needs to be considered, namely that due to *expansion.*

The accompanying photograph of a polygonal structure in a cement briquette (Fig. 4) is an illustration of the formation of this structure by internal expansion. This sample, which was kindly furnished us by Mr. A. A. Klein, of the Bureau of Standards in Pittsburgh, was made from a cement which contained free lime; this by its hydration and absorption of carbon dioxide from the air has expanded and destroyed the briquette.

It is possible that the "weather-crack" structure on the surface of diabase bowlders is likewise caused by internal expansion. Wherry[3] has shown that there is no visible difference in texture underlying these weather-cracks. Expansion of the surface by hydration has been assumed as the cause of the structure; but this would produce *compression* in the surface, accompanied by the formation of shells (as indeed often occurs), whereas the "weather-crack" structure is one indicating *tension.* It is necessary for hydration to proceed into deeper portions of the rock before tension

[1] *Soc. Geol. France, Compt. rend. somm.*, 1912, pp. 181–83; *Bull.*, XIII (1913), 33–38.

[2] *Proc. Boston Soc. Nat. Hist.*, XXVII (1896), 163–83. For an extended study of these feather fractures in glass and metals see Ch. de Fréminville, "Recherches sur la fragilité; L'éclatement," *Rév. metallurgie*, 1914; also Mallock, *Proc. Roy. Soc.*, A, LXXXII (1909), 26–29.

[3] *Loc. cit.*

is set up in the surface; the cracks then produced are soon widened by solution. A photograph of an excellent example of this type of structure in diabase is given in Fig. 5. Internal expansion may also account for the prismatic surface structure of "bread-crust bombs," although this remains to be proved.

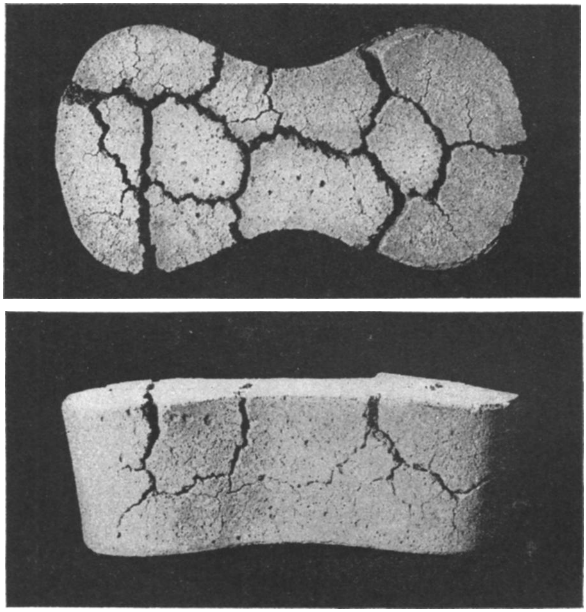

FIG. 4.—A polygonal structure in a cement briquette, caused by internal expansion.

SUMMARY

From the physical standpoint, several types of prismatic structure in igneous rocks can be distinguished. The first and most common is due purely to thermal contraction in the crystallized rock; examples are numerous and familiar. A subordinate type of contraction structure is produced when the contraction and separation occur while the magma is still partly crystalline and partly liquid; this type is illustrated by an occurrence in a diabase sill in eastern Pennsylvania.

FIG. 5.—"Weather-crack" structure on the surface of a diabase bowlder

The second general type is produced by convectional circulation of the magma while still liquid. The cells so produced persist until solidification begins, and may leave a record in the rock either by causing segregation in the cell walls and axes, or by originating regularly spaced centers of crystallization. The experimental and observational data on the occurrence of this type in igneous rocks are suggestive, but cannot yet be said to amount to decisive proof.

A third type of prismatic structure is produced by internal expansion. It has been produced artificially, and is offered as the explanation of the "weather-crack" structure seen in diabase bowlders.

In the study of these structures, the following field observations are those which will be of greatest interest in the further study of the problem: (1) attitude of prisms, (2) their diameter and length, (3) frequency of four-, five-, six-, and seven-sided polygons, (4) frequency of angles (especially 90° and 120°), (5) variation, if any, of composition and texture in the cross-section, (6) types of cross-jointing (platy, concave or convex, spheroidal), (7) spacing of cross-joints, (8) peculiarities of cross-joints (e.g., whether cracked from center or from borders), (9) degree of irregularity in sides of prisms, (10) other peculiarities, such as tapering, partial longitudinal jointing, etc.

The primary object of this discussion is to call attention to the possibilities of the prismatic structure of a given rock body as an index of its conditions of formation. Quantitative data on columnar structures are very scarce; yet quantitative measurements must precede quantitative deductions. We wish to know the temperature of the rock when it was intruded or extruded; its viscosity when it began to cool and when it began to crystallize; the amount and kind of gases which it released; if extrusive, the climatic conditions under which it cooled; if intrusive, the properties of its inclosing strata at the time of intrusion. These and other facts are deducible only from the present properties of the rock, among which its prismatic structure will prove of great importance.

Equally necessary with the field data are experimental studies of the structures produced in a cooling magma under conditions

that can be controlled and measured. Such experiments will require the melting and handling of larger quantities than it has been customary to use for laboratory experiments, but the difficulties ought not to prove serious. Even in the absence of such experimental data, much can be learned from a careful field examination of prismatic and columnar structures.